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Analysis of Inclined Air Shower Events Observed by the TA×4 SD

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The TA×4 upgrade, which has been ongoing since a portion of the detectors were newly installed in 2019, aims to reveal the origin of UHECRs by expanding the detection area of the Telescope Array (TA) experiment by a factor of four and increasing the number of observed events. In the analysis of the TA×4 surface detector array (TA×4 SD) data, we extended the zenith angle limit of the energy estimation table generated from Monte Carlo simulation (MC) from 55 to 70 degrees, in order to increase the detector sensitivity further. We also compared the results from observed data and simulation for each parameter obtained using the extended reconstruction method and confirmed that there were no significant discrepancies between them. Furthermore, we measured the energy spectrum, using large zenith angle events up to 65 degrees in zenith angle, based on three years of the TA×4 SD data.

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1. Introduction

The origin of ultrahigh-energy cosmic rays (UHECRs) has not yet been revealed. The Telescope Array (TA) experiment has observed cosmic rays with both surface detector arrays and fluorescence detectors in the Northern Hemisphere for more than 15 years. Previous observations of the TA experiment have shown indications of the anisotropy in the arrival directions of UHECRs. In particular, the arrival directions of cosmic rays above 57 EeV indicated an intermediate scale anisotropy with $3.4\,\sigma$ global significance [1], known as the TA hotspot. However, they have not been confirmed due to insufficient statistical significance. To increase the number of observed events, some detectors were newly constructed in 2019 by the TA×4 upgrade, which will expand the total detection area of the TA experiment by a factor of four to $2800\,\mathrm{km}^2$. The current standard reconstruction of air shower events with the TA×4 surface detector array (TA×4 SD) uses events with zenith angles up to 55 degrees.

In this paper, we increase the number of observed events by extending the energy estimation table generated from Monte Carlo simulation (MC) to 0-70 degrees in zenith angle, and including all observed events in this range for analysis. To validate the accuracy of the simulated energy estimation table, we also perform Data/MC comparisons. Finally, we measure the TA×4 SD energy spectrum using this expanded data set.

2. Reconstruction of air shower events observed by the TA×4 SD

The reconstruction method for the TA×4 SD is basically the same as that of the TA SD [2]. The only difference is the energy estimation table, which is used to determine the energy of air shower events. Both energy estimation tables are generated from Monte Carlo simulation, but in the case of the TA×4 SD, QGSJETII-04 [3] is assumed as a hadronic interaction model in the shower generation by CORSIKA [4]. The energy of the air shower with a zenith angle of up to 60 degrees can be determined using the original energy estimation table [5]. In the analysis of the TA×4 SD, the reconstruction method has previously been established for zenith angles up to 55 degrees.

3. Extension of the energy estimation table for the TA×4 SD

To enable the reconstruction of large zenith angle events above 60 degrees, we extended the original energy estimation table to even larger zenith angles. We used the same simulation data set as the original energy estimation table for the TA×4 SD [5]. Event selection is performed under the same selection criteria as [5] but now accepting all simulation data up to 70 degrees in zenith angle. The simulation data are binned in 1/10 decade logarithmic steps in energy, and by 0.02 increments in $\sec\theta$, secant of the zenith angle. The mean values of particle density S_{800} are calculated for each bin. These mean S_{800} values are plotted against $\sec\theta$ and fitted using 4th-degree polynomial functions, respectively for each energy. Finally, fit results are plotted together and smoothed by two-dimensional interpolation as shown in Figure 1. This energy estimation table can be used to determine the energy of the primary cosmic ray in the range of $10^{19.5}$ eV – $10^{20.5}$ eV in energy and 0-70 degrees in zenith angle.

After extending the energy estimation plot, we also evaluated the reconstruction accuracies of the TA×4 SD. We compared the generated and reconstructed values for each reconstructed parameter

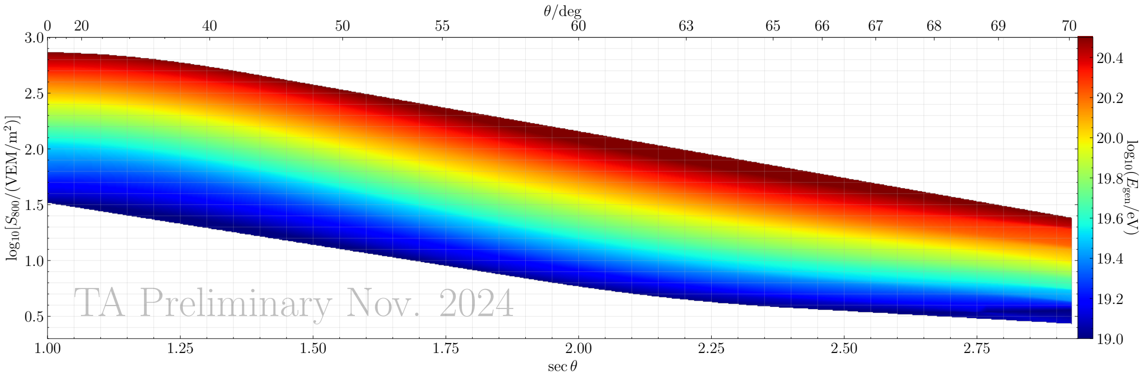
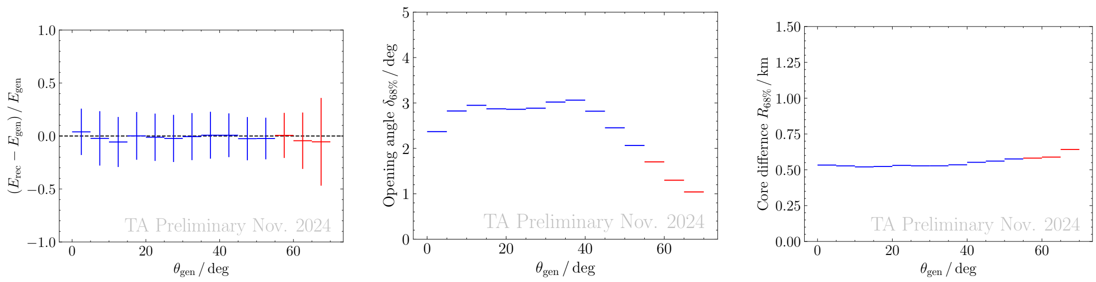


Figure 1: The extended energy estimation plot for the TA×4 SD. The horizontal axis shows the zenith angle ($\sec\theta$) and the vertical axis shows particle density (S_{800}). The colors indicate the energy of the primary cosmic ray.

using simulation as shown in Figure 2. These show (a) the relative error between the generated and reconstructed energies of the primary cosmic rays, (b) the opening angle between the generated and reconstructed arrival directions, and (c) the difference between the generated and reconstructed core positions. We evaluated these accuracies for each zenith angle, respectively. From these plots, we conclude that reconstruction accuracies of large zenith angle events are comparable to those of conventional zenith angle regions.



(a) Energy **(b)** Opening angle **(c)** Core difference

Figure 2: The result of the evaluation of reconstruction accuracies for each zenith angle. Here examples for $10^{20.1}$ eV are shown. The points over 55 degrees in the zenith angle are marked in red instead of blue.

4. Data/MC comparison

We use MC to generate the energy estimation table and calculate an exposure of the TA×4 SD. Therefore, it is necessary to confirm that MC reproduces observed data accurately. To this end, we performed Data/MC comparisons. Event selection criteria are the same as the previous analysis with the TA×4 SD, except for the extended zenith angle range. We compared distributions of the observed data and simulation for six parameters obtained using the extended reconstruction method. These are shown in Figures 3 and 4, for the entire range of zenith angles of 0-65 degrees and only for the range of 55-65 degrees, respectively.

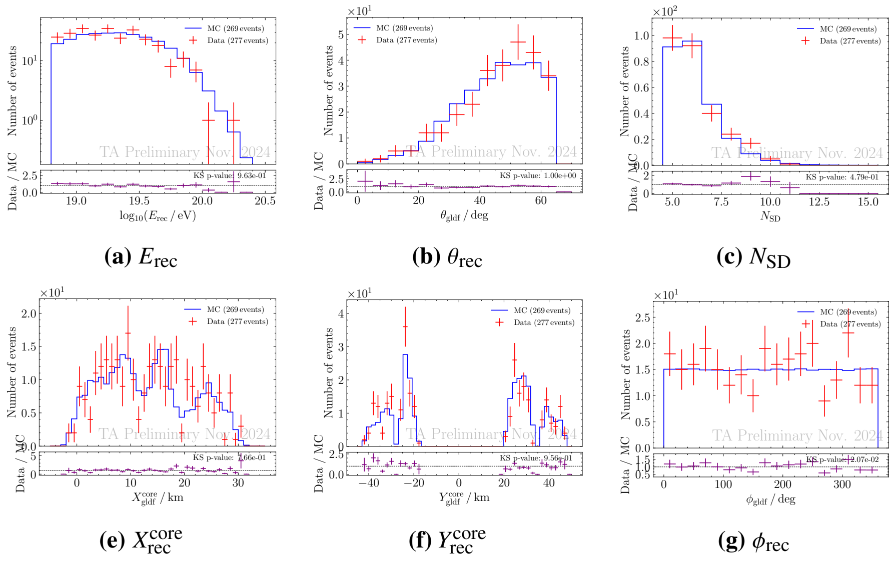


Figure 3: Comparison between observed data (red points) and simulation (blue histograms) for "all" events including large zenith angle events. The ratios of observed data and simulation (purple points) are also shown. Reconstructed parameters are (a) the energy determined by the extended energy estimation table, (b) the zenith angle, (c) the number of SDs used for the reconstruction, (d) (e) the core positions ($X^{\rm core}_{\rm rec}$ as east-west direction and $Y^{\rm core}_{\rm rec}$ as north-south direction), and (f) the azimuthal angle. The subscript "gldf" means the result from the combined fit of geometry and lateral distribution. Kolmogorov–Smirnov test p-values are shown in the sub-plots.

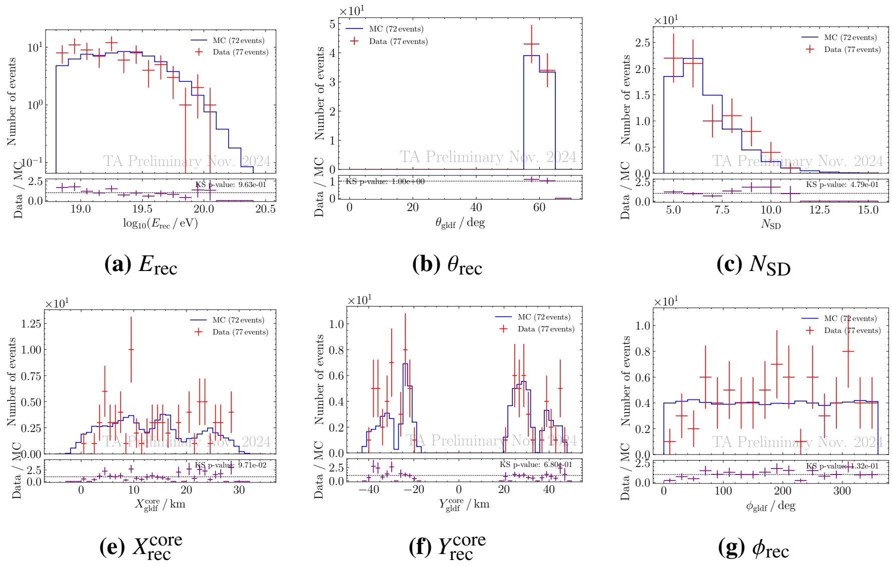


Figure 4: Comparison between observed data (red points) and simulation (blue histograms) "only" for large zenith angle events (55-65 degrees). Reconstructed parameters are the same as those in Figure 3.

Histograms of the simulation are normalized to match the expected number of events calculated using the energy scale factor 1.36 (this is the value calculated in the previous analysis [5] using events below 55 degrees in zenith angle) and assuming the TA SD 11-year energy spectrum [6]. There is no significant discrepancy between the observed data and simulation even with only large zenith angle events. This result indicates that MC reproduces accurately observed air shower events.

5. Energy spectrum

The cosmic ray energy spectrum is obtained using the following equation:

$$J_i = \frac{\frac{\left(N_{\rm rec}^{\rm Data}\right)_i}{\Delta E_i}}{\frac{\left(N_{\rm rec}^{\rm MC}(E_{\rm rec})\right)_i}{\left(N_{\rm gen}^{\rm MC}(E_{\rm gen})\right)_i} A_{\rm gen}\Omega_{\rm gen} T} \tag{1}$$

where $N_{\rm rec}^{\rm Data}$ is the number of observed events in each energy bin, $A_{\rm gen}\Omega_{\rm gen}$ is the geometrical aperture of TA×4 SD calculated from the area and solid angle in which MC is generated, T is the observation period, and $(N_{\rm rec}^{\rm MC}(E_{\rm rec}))_i/(N_{\rm gen}^{\rm MC}(E_{\rm gen})_i$ is the reconstruction efficiency that includes the consideration of bin-to-bin migration effects. Effective exposures are calculated from simulation and shown in Figure 5.

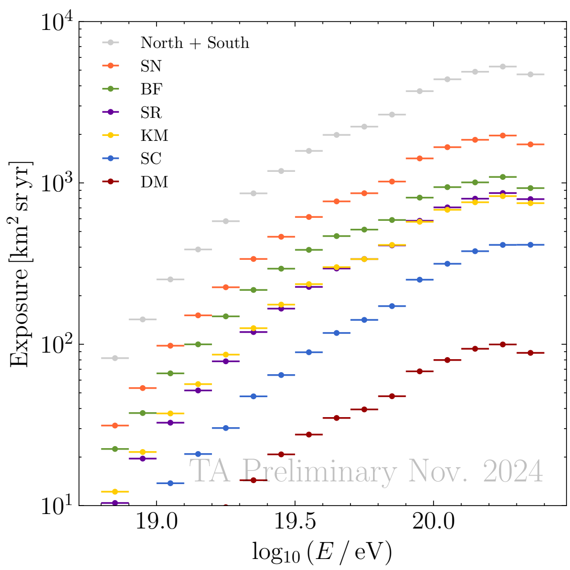


Figure 5: Effective exposure calculated from Monte Carlo simulation. The colored points show the individual exposures of the six sub-arrays that comprise the current configuration of the TAx4 SD

Figure 6 is the result of the first measurement of the TA×4 energy spectrum, using large zenith angle events up to 65 degrees. These are based on three years of observation from October 2019 to September 2022. The energy spectrum of the previous analysis with the TA×4 SD using air shower events below 55 degrees in zenith angles [5] and the TA SD 14-year energy spectrum (zenith angles are below 45 degrees) [7] are also shown. The new result with the extended zenith angle range shows good agreement with the previous analyses.

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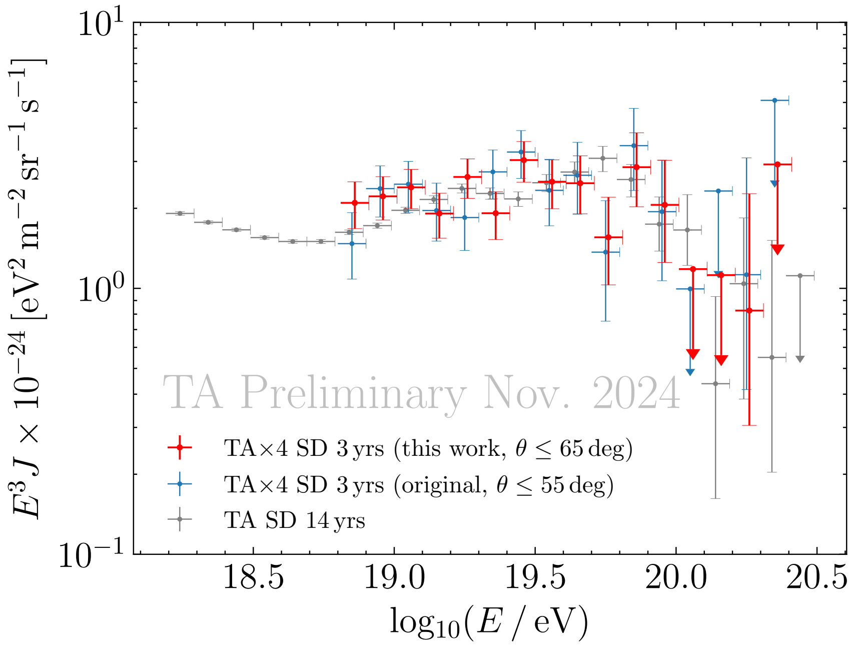

Figure 6: Energy spectrum measured in this work (red points). the TA×4 SD previous analysis (blue points) and the TA SD 14-year energy spectrum (gray points) are also shown.

6. Summary

In this paper, we extended the zenith angle limit of the energy estimation table. We also compared the results from the observed data and simulation for each parameter obtained using the extended reconstruction method and confirmed no significant discrepancies between them. Furthermore, we measured the energy spectrum using large zenith angle events, based on three years of the TA×4 SD data. It showed good agreement with the previous analyses.

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